

MULTI-CHANNEL AUDIO SURROUND SOUND FROM FRONT LOCATED LOUDSPEAKERS

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BACKGROUND OF THE INVENTION

Field of the Invention

[0001] This invention relates generally to the reproduction of sound in multichannel systems generically known as “surround-sound” systems and more specifically to the application of psychoacoustic principles in the design of a loudspeaker system for reproducing a surround sound experience from loudspeakers located only in front of the listener.

Background Art

[0002] It has long been recognized that it is possible to use interaural crosstalk cancellation (IACC) and head related transfer functions (HRTF) to expand the perceived soundstage of a two channel audio system or to create the illusion of sounds coming from phantom locations independent of the actual location of the loudspeakers. Through the 1970’s and 1980’s a number of audio components were available for purchase which used IACC to expand the perceived soundstage. However, until the availability of inexpensive, powerful digital signal processing (DSP) more accurate generation of phantom sound sources at specific locations was very difficult and costly due to the complexity of accurate HRTF synthesis.

[0003] More recently the availability of DSP and improved filtering algorithms has made it possible to create a phantom sound source in almost any location using just a single pair of loudspeakers typically located in front of the listener. Using variations of the same techniques it is possible to create several phantom

sound sources at the same time from a single pair of loudspeakers typically located in front of the listener. This technique has many practical applications. For example, the experience of having front, rear and center speakers as in a complete 5.1 surround sound audio system can be simulated using a single pair of loudspeakers or headphones.

[0004] These techniques are based on the way in which human beings process sounds received by their ears to determine the location of the sources of those sounds. In general, we hear the direction of sounds based on two primary mechanisms, Interaural Time Delays (ITD) and Interaural Level Differences (ILD). ITD refers to the additional time required for a sound located to one side of the listeners head to arrive at the opposite side ear as compared to the time required to reach the near side ear. The ITD of a sound allows the listener to determine the lateral direction of a sound with great precision. ILD refers to the difference in perceived intensity between the listeners two ears for a sound arriving from a particular location. For example, a sound located to the listeners left would appear generally louder in the left ear as compared to the right ear due to a reduction in loudness as the sound passes across the listener's head. Overall intensity differences between the ear reinforce lateral localization of sounds through ITD's. In addition, sounds arriving from a particular direction produce a complicated frequency response pattern at each ear which is characteristic of that specific directional location. The combination of these characteristic directional frequency response curves and the ITD's associated with sounds arriving from that direction are referred to as Head Related Transfer Functions (HRTF). The frequency response component of the HRTF's is quite complex and somewhat different for each individual. It is the detailed structure of the HRTF

frequency response at each ear that allows the listener to determine the elevation of a sound and whether it is in front or behind. For example, a sound source located 60 degrees to the left and in front of the listener has the same ITD (approx. 300 ms) as a sound source located at 60 degrees left and behind the listener. However, the asymmetry of the outer ear produces very different HRTF's for those two sound source locations thereby allowing the listener to

determine both the lateral location and front versus back. A similar mechanism allows the listener to determine the approximate elevation of a sound source. In general the mechanism for determining lateral location of sounds based on ITD's operates in the frequency range of approximately 150Hz to 1,200Hz. The mechanisms for localizing sounds based on the frequency response of HRTF's operates from approximately 500Hz to above 12,000Hz.

[0005] Based on these principles various methods have been devised for canceling interaural crosstalk in loudspeakers, generating phantom sound sources from monaural signals using synthetic or measured HRTF's and for using HRTF's to create phantom rear channels for an audio surround sound system from only a front pair of speakers.

[0006] In general, methods using HRTF's to create phantom sound sources, whether for simulation of a surround sound audio system or other application, have a number of practical limitations. Accurate representation of HRTF's is very computation intensive and it is therefore difficult to obtain sufficient accuracy using practical and cost efficient DSP methods. For example, U.S. Patent No. 6,173,061, which describes a method for phantom sound source generation using HRTF's, acknowledges the need for more efficient sound processing algorithms and seeks to address this problem. Additionally, the specific HRTF's used in prior art methods are selected on the basis

of assumptions regarding the characteristics of the loudspeakers employed, the specific positional relationship between the loudspeakers and the listener, and the variation of actual HRTF's from listener to listener. Given the highly specific and detailed nature of HRTF's, those skilled in the art will recognize that changes in the loudspeaker characteristics or locations combined with movement of the listener away from the assumed listening location can easily destroy the phantom sound source illusion. Also, the actual HRTF's of some listeners may be too different from the HRTF's employed

in the device for the illusion to work. For example, U.S. Patent No. 4,893,342 and its related patents describe methods for increasing the positional flexibility of an HRTF based method by limiting the frequency range of the HRTF representations to a range of approximately 600Hz to 10kHz and methods for determining listener tolerant HRTF's.

[0007] Some known methods for creating phantom sound locations and sources rely on the use of binaurally recorded signals or other specially recorded signals as inputs. These methods may be subject to the above described limitations and will also function properly only when using input signals made with the specified recording scheme. For example, U.S. Patent No. 4,199,658 describes such a method based on the use of binaurally recorded signals as inputs.

[0008] Finally, most known methods for creating phantom rear channel sound sources seek to reproduce the illusion that actual loudspeakers are located at specific locations behind the listener. Such methods are disclosed, for example, in U.S. Patent No. 6,052,470 and its related patents which describe various methods for using HRTF's to create the illusion of a pair of speakers located behind the listener. However, those skilled in the art generally agree that in rear channel sound reproduction for an audio

surround sound system, diffuse localization is preferable to the type of specific localization provided by actual rear located direct radiator loudspeakers. Furthermore, as will be understood by those skilled in the art, audio surround sound systems composed of front and rear pairs of speakers are not effective in localizing sounds in the general areas

directly to the left and right of a listener located centrally between the two pairs of speakers.

[0009] Therefore, there exists a need for methods for creating phantom rear surround sound channels which require less complicated signal processing, which are more tolerant of loudspeaker characteristics, loudspeaker placement, listener location and listener to listener HRTF variations, which are effective when using commonly available recordings and which are capable of diffuse localization of rear channel sounds in an audio surround sound system over a range of locations around the listener.

BRIEF SUMMARY OF THE INVENTION

[0010] Therefore, it is an object of this invention to provide a device and method for producing phantom rear surround sound channels or a phantom surround sound effect from a loudspeaker system or pair of loudspeaker systems located in front of the listener. An additional object of this invention is to permit implementation using simple analog filters or simple DSP. It is another object of the present invention to be more tolerant of loudspeaker characteristics, loudspeaker placement, listener location and listener to listener variation. Yet another object of this invention is to create effective surround sound reproduction when using commonly available audio surround sound recordings. A further object of this invention is to generate phantom sound sources that are perceived

as originating from a range of different locations around or behind the listener including the general areas directly to the left and right of the listener.

[0011] U.S. Patent Nos. 4,489,432; 4,497,064; 4,569,074 and 4,630,298 disclose a method for using an arrangement of main and sub-speakers in a stereo sound reproduction system to cancel IAC and to produce a realistic acoustic field extending beyond the loudspeaker locations using signals from commonly available stereo recordings. The disclosures of these patents are incorporated herein in their entirety by reference. For example, prior art FIG. 1 (FIG. 10 of U.S. Patent No. 4,489,432) shows specifically how an arrangement of main and sub-speakers can be used to create a phantom sound source outside the boundaries of the loudspeaker locations from two input signals. Based on the disclosures of U.S. Patent Nos. 4,489,432; 4,497,064; 4,569,074 and 4,630,298 it will be apparent to those skilled in the art that a system constructed in accordance with these disclosures is capable of creating phantom sound sources anywhere in front of the listener more or less independent of the loudspeaker locations according to the localization information contained in the two recorded signals used as inputs. The methods described in these patents are also capable of creating a stable sound image when no localization information exists in the two recorded signals used as inputs.

[0012] In accordance with one embodiment of the present invention, in an audio reproduction system having at least four inputs for accepting at least four audio input signals, for example, left front, right front, left surround and right surround channel signals, a right main speaker and a left main speaker are provided respectively at right and left main speaker locations along a speaker axis which are equidistantly spaced from the principle listening location. The principle listening location **LL** is generally defined as a spatial position for accommodating a listener's head facing the main

speakers along a central listening axis and having a right ear location and a left ear location along an ear axis, with the right and left ear locations separated by a maximum interaural sound distance of Δt_{max} and the principle listening location is specifically defined as the point on the ear axis equidistant to the right and left ears. The central listening axis **CLA** is defined as a line passing through the principle listening location and a point on the speaker axis equidistant from the right and left main speakers. A right sub-speaker and a left sub-speaker are provided at right and left sub-speaker locations substantially on the speaker axis of the left and right main speakers and which are equidistantly spaced from the principle listening location **LL**. By careful location of the sub-speakers relative to the main speakers, use of proper modifications and combinations of the left and right surround signals to create driving signals for the main and sub-speakers, and appropriate filtering of the component parts of said driving signals, a listener located in the principle listening location **LL** perceives a surround sound experience from speakers located only in front of the listener.

BRIEF DESCRIPTION OF THE DRAWINGS/FIGURES

[0013] FIG. 1 is a diagram illustrating an apparent source location as produced by the arrangement disclosed in U.S. Patent No. 4,489,432, FIG. 10.

[0014] FIG. 2 is a diagram showing a first embodiment of the present invention.

[0015] FIG. 2a is a diagram showing the signal combinations of a first embodiment of the present invention.

[0016] FIG. 2b is a diagram showing the addition of a fifth audio input signal to the first embodiment of the present invention.

[0017] FIG. 3 shows a family of frequency response curves of sounds incident from various angular directions.

[0018] FIG. 4 shows a family of frequency response curves showing frequency response differences between sounds incident from in front of a listener and behind the listener, at the near ear of the listener.

[0019] FIG. 5 shows a family of frequency response curves showing frequency response differences between sounds incident from in front of a listener and behind the listener, at the far ear of the listener.

[0020] FIG. 6 shows a family of frequency response curves representing the differences between the front-to-back curves for the near ear shown in FIG. 4 and the front-to-back curves for the far ear shown in FIG. 5 for each mirror image front to back pair of sound locations.

[0021] FIG. 7 is a schematic diagram showing perceived rear sounds at a point location behind the listener.

[0022] FIG. 8 is a schematic diagram showing perceived apparent sound locations over a broad range of locations begin the listener when utilizing the present invention.

[0023] FIG. 9 shows a family of curves calculated by subtracting the frequency response shown in FIG. 3 for sounds arriving from a particular direction at the listener's nearest ear from the frequency response for sounds arriving from the same direction at the listener's farthest ear.

[0024] FIG. 10 is a diagram showing a second embodiment of the present invention.

[0025] FIG. 11 is a diagram showing a third embodiment of the present invention.

[0026] FIG. 12 is a diagram showing a fourth embodiment of the present invention.

[0027] FIG. 13 is a diagram showing a fifth embodiment of the present invention.

[0028] FIG. 13a is a diagram showing the signal combinations of a fifth embodiment of the present invention.

[0029] FIG. 14 is a diagram showing approximate perceived sound locations in front of the listener and apparent perceived sound locations to the rear of the listener when using a fifth embodiment of the present invention.

[0030] FIG. 15 is a diagram showing a sixth embodiment of the present invention.

[0031] FIG. 16 is a diagram showing approximate perceived sound locations in front of the listener when using a sixth embodiment of the present invention.

[0032] FIG. 17 is a diagram showing an seventh embodiment of the present invention.

[0033] FIG. 18 is a diagram showing approximate apparent perceived sound locations to the rear of the listener when using an seventh embodiment of the present invention.

[0034] FIG. 19 is a diagram showing a eighth embodiment of the present invention.

[0035] FIG. 20 is a diagram showing the signal combinations of a ninth embodiment of the present invention.

[0036] FIG. 21 is a diagram showing a tenth embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0037] Preferred embodiments of the present invention are now described with reference to the figures where like reference characters/numbers indicate identical or functionally similar elements. While specific configurations and arrangements are discussed, it should be understood that this is done for illustrative purposes only. A person skilled in the relevant art will recognize that other configurations and arrangements can be used without departing from the spirit and scope of the invention.

[0038] FIG. 2 and FIG. 2a show a first preferred embodiment of the present invention. Referring to FIG. 2, four audio signal inputs, for example only and not by way of limitation, corresponding to signal channels of a surround sound system are provided. It is understood that these may be any four audio input signals. However, for

purposes of clarity and consistency these signals will be referred to herein as left surround signal **LS**; left front signal **LF**; right front signal **RF**; and right surround signal **RS**. Left and right loudspeaker enclosures, **LSE** and **RSE** are also provided. Left loudspeaker enclosure **LSE** contains at least one left main speaker **LMS** and at least one left sub-speaker **LSS**. Right loudspeaker enclosure **RSE** contains at least one right main speaker **RMS** and at least one right sub-speaker **RSS**. As is well known by those skilled in the art unmodified audio signals reproduced by a pair of of loudspeakers, such as in a typical stereo audio system, are perceived by a listener sitting in front of the speakers as originating from a range of sound locations between the two loudspeakers. Therefore, sounds produced only by main left and right loudspeakers **LMS** and **RMS** are perceived by a listener located at principle listening location **LL** as originating from a range of sound locations approximately between and bounded by the actual locations of left and right main loudspeakers **LMS** and **RMS**.

[0039] As shown in FIG. 2, a listener located at principle listening location **LL** has a left ear **Le** and a right ear **Re**. The midpoint between the left ear **Le** and the right ear **Re** is located along a central listening axis **CLA**. As noted in U.S. Patent No. 4,489,432, incorporated in its entirety by reference herein, the right and left ear locations are separated by a maximum interaural sound distance of Δt_{max} . As also explained in U.S. Patent No. 4,489,432, and shown in FIG. 2, sound distance **t** is the time for sound from the left main speaker **LMS** to reach the left ear **Le** and sound distance **t+Δt** is the time for sound from the left main speaker **LMS** to reach the right ear **Re**. Similarly, sound distance **t** is also the time required for sound from right main speaker **RMS** to reach right ear **Re** and sound distance **t+Δt** is also the time for sound from the right main speaker **RMS** to reach the left ear **Le**. In similar fashion, **t+Δt** is

also the time for sound from the right sub-speaker **RSS** to reach the right ear **Re**, and the time for sound from the left sub-speaker **LSS** to reach the left ear **Le**.

[0040] Referring again to FIG. 2, left surround signal **LS** passes through front-to-back filter 1 and is combined with left front signal **LF** in adder 3. The combined signal is then transmitted to left main speaker **LMS**. Similarly, right surround signal **RS** passes through front-to-back filter 2 and is combined with right front signal **RF** in adder 4. The combined signal is then transmitted to right main speaker **RMS**.

[0041] Front-to-back filters 1 and 2 modify the surround signals **LS** and **RS** such that, at the listeners ears and over a certain frequency range, they will approximate the frequency response of sound signals as if they originated from the rear of the listener, even though they are being projected from the front of the listener. This modification is explained with reference to FIGS. 3 to 6. FIG. 3 shows a family of frequency response curves representing the frequency response at the ear drum of a listener relative to free field conditions for sounds arriving from different angular sound locations in the horizontal plane. FIG. 4 shows another family of frequency response curves calculated by subtracting the frequency response from FIG. 3 for sounds arriving at the listener's nearest ear of sound locations in front of the listener from the frequency response for sounds arriving from a mirror image sound location behind the listener. For example, referring to FIG. 3, subtracting the curve for sounds arriving at the listeners left ear at an angle of 45 degrees, in front of the listener, from the curve for sounds arriving at the left ear at an angle of 135 degrees, behind the listener, produces the curve labeled "45-135 deg." in FIG. 4. Thus, with the front-to-back filters 1 and 2 of FIG. 2 having the approximate characteristics of, for example, the front-to-back frequency response curve from FIG. 4 labeled "45-135 deg." and left and right main speakers **LMS** and **RMS** located approximately 45 degrees to either

side of central listening axis **CLA**, a listener located at the principle listening location **LL** will perceive approximately the same frequency response for surround signals **LS** and **RS** at the ear drum of the respective nearest ear as if these sounds were originating at sound locations behind the listener mirror imaged to the actual sound locations of **LMS** and **RMS** in front of the listener from which the surround signals **LS** and **RS** are actually emanating.

[0042] FIG. 5 shows a similar family of front-to-back frequency response curves calculated by subtracting the frequency response shown in FIG. 3 for sounds arriving at the listener's farthest ear of sound locations in front of the listener, from the frequency response for sounds arriving from mirror image sound locations behind the listener. Application of front-to-back filters with these characteristics to sounds arriving at the listener's farthest ear from actual sound locations in front of the listener will duplicate the frequency response at the listener's farthest ear drum of a sound arriving from a mirror image sound location behind the listener. For example, referring again to FIG. 3, subtracting the curve for sounds arriving at the listeners left ear at an angle of minus 45 degrees, in front of the listener, from the curve for sounds arriving at the left ear at an angle of minus 135 degrees, behind the listener, produces the curve labeled "45-135

deg." in FIG. 5. Thus, with front-to-back filters 1 and 2 of FIG. 2 having the approximate characteristics of, for example the front-to-back frequency response curve from FIG. 5 labeled "45-135 deg." and left and right main speakers **LMS** and **RMS**, located approximately 45 degrees to either side of central listening axis **CLA**, a listener located at principle listening location **LL** will perceive approximately the same frequency response for surround signals **LS** and **RS** at the ear drum of the respective farthest ear as if the sound were located at sound locations behind the

listener mirror imaged to the actual sound locations of **LMS** and **RMS** in front of the listener from which the surround signals **LS** and **RS** are actually emanating.

[0043] FIG. 6 shows a family of frequency response curves representing the differences between the front-to-back curves for the near ear shown in FIG. 4 and the front-to-back curves for the farthest ear shown in FIG. 5 for each mirror image front to back pair of sound locations. It can be seen by inspection of FIG. 6 that the front-to-back curves for the near ear and far ear are substantially the same up to a frequency of approximately 2,500 Hz. It can also be seen by inspection of FIG. 4 and FIG. 5 that the front-to-back frequency response curves for both the near ear and the far ear are very similar up to a frequency of approximately 2,500 Hz for sound locations approximately between 30 degrees and 60 degrees either side of central listening axis **CLA** in front of the listener. If front-to-back filters **1** and **2** have the approximate characteristics of, for example the front-to-back frequency response curve from FIG. 4 labeled '45-135 deg.' up to an approximate frequency of 2,500 Hz, then a listener located at the principle listening location **LL** will perceive approximately the same frequency response up to approximately 2,500 Hz at both ear drums for signals modified by said front-to-back filters **1** and **2** as if the sound were located at sound locations behind the listener mirror imaged to the actual sound locations of left and right main speakers **LMS** and **RMS** in front of the listener for locations of left and right main speakers **LMS** and **RMS** approximately between 30 degrees and 60 degrees to either side of the central listening axis **CLA**. As shown in FIG. 7 if the input signals to front-to-back filters **1** and **2** are, for example, the left and right surround signals **LS** and **RS**, the listener will perceive that the left and right surround signals **LS** and **RS** are being produced by loudspeakers located at mirror image locations phantom left and right speakers **PLS** and **PRS** behind the listener.

[0044] Therefore, in this first embodiment the front-to-back filters 1 and 2 of FIG. 2 may have characteristics which limit the frequency range to below approximately 2,500 Hz and which have approximately the frequency response of the curve labeled "45-135 deg." in FIG. 4 for frequencies below approximately 2,500 Hz. As noted above and as shown in FIG. 6, because front-to-back frequency response curves are very similar below approximately 2,500 Hz over a range of angular locations and for both near and farthest ear, even if the speakers are not located at exactly 45 degrees from the central listening axis **CLA**, the front-to-back filters 1 and 2 will still cause the listener to perceive that sounds are coming from mirror image locations behind the listener, as shown in FIG. 7. Notwithstanding the foregoing discussion, experiments have shown that in some implementations of the present invention it is desirable for the frequency response of front-to-back filters 1 and 2 to extend substantially above 2,500 Hz. It has also been found that, in some implementations it is desirable to include a band emphasis of approximately plus 4 db to plus 8 db at a frequency of approximately 12 kHz.

[0045] Referring again to FIG. 2, after passing through front-to-back filter 1, left surround signal **LS** passes through an inverter 5 and a low pass filter 11. It then passes through an adder 10, in which it is combined with right surround signal **RS**, which has passed through front-to-back filter 2 and low pass filter 8 such that the resulting combined signal is composed of a modified left surround signal **LS'** subtracted from a modified right surround signal **RS'**. The combined signal is then transmitted to right sub-speaker **RSS**, located in right speaker enclosure **RSE**. Similarly, after passing through front-to-back filter 2, right surround signal **RS** passes through an inverter 6 and a low pass filter 12. It then passes through an adder 9, in which it is combined with left surround signal **RS**, which has passed through front-to-

back filter 1 and low pass filter 7 such that the resulting combined signal is composed of a modified right surround signal **RS'** subtracted from a modified left surround signal **LS'**. The combined signal is then transmitted to left sub-speaker **LSS** located in left speaker enclosure **LSE**. Low pass filters 7, 8, 11 and 12 may have characteristics limiting the frequency response to below approximately 1 kHz, as disclosed in U.S. Patent No. 4,630,298 generally for the purpose of stabilizing the apparent sound locations, improving tolerance to movements of the listener's head, improving the illusion of apparent sound locations for listeners not located at the principle listening location **LL**, and allowing greater tolerance in the location of the main and sub-speakers. However, in some implementations of the present invention it is desirable for said low pass filters to have frequency response extending substantially beyond 1 kHz or to select one cutoff frequency for low pass filters 7 and 8, and a different cutoff frequency for low pass filters 11 and 12. In one specific implementation of this embodiment of the present invention low pass filters 7 and 8 have a frequency response extending to approximately 5 kHz and low pass filters 11 and 12 have a frequency response extending up to approximately 1.8 kHz.

[0046] In accordance with this first embodiment, FIG. 2a shows the general composition of the modified and combined signals transmitted to each speaker where the prime designation, ', denotes that the original audio input signal has been suitably modified by signal modification and combination means 20. It will be understood that within the scope of the present invention and as shown in FIG. 2a that any suitable means may be employed to achieve the appropriate signal modifications and combinations. In addition and as discussed above, experiments have shown that within the scope of the present invention, many variations to the specific signal modifications herein described function to provide an acceptable surround sound

illusion from loudspeakers located only in front of the listener. The specific signal modifications described herein are by way of example only and not of limitation.

[0047] In this first embodiment, left sub-speaker **LSS** and right sub-speaker **RSS** are positioned relative to left main speaker **LMS** and right main speaker **RMS** and to the listener according to the teachings of U.S. Patent Nos. 4,489,432; 4,497,064; 4,569,074 and 4,630,298 for the purpose of canceling IAC and producing a realistic acoustic field extending beyond the loudspeaker locations. As shown in prior art Fig. 1, and discussed in the above-referenced U.S. Patents, the left and right sub-speakers **LSS** and **RSS** may be located on a common speaker axis with left and right main speakers **LMS** and **RMS**. However, as also discussed in the above-referenced U.S. Patent No. 4,497,064, the sub-speakers may be placed in any location that produces the correct time delay relative to the respective main speakers for sounds aiming at the listener's ears. As shown in FIG. 2 and discussed in U.S. Patent Nos. 4,489,432; 4,497,064; and 4,569,074 in the case that the main and sub-speakers are located along a common speaker axis the preferred spacing between the respective main and sub-speakers on each side is approximately equal to the maximum interval sound Δt_{\max} up to approximately 150% of Δt_{\max} resulting in a corresponding variation in the inter-speaker delay Δt without departing from the spirit and function of the present invention. As shown in prior art FIG. 1, the methods disclosed in U.S. Patent Nos. 4,489,432; 4,497,064; 4,569,074 and 4,630,298 are capable of creating apparent sound locations in a range of up to approximately 90 degrees left and right of central listening axis **CLA** in front of the listener from two audio input signals such as are present in a normal stereo recording. As previously described, in the first embodiment of the present invention, front-to-back filters 1 and 2 of FIG. 2 are selected to transform the frequency response of sound locations in front of the listener to

approximate the frequency response at both of the listener's ear drums of sound locations at mirror image locations behind the listener over a defined frequency range. The methods disclosed in U.S. Patent Nos. 4,489,432; 4,497,064; 4,569,074 and 4,630,298 modified as specified herein and in combination with the aforementioned signal manipulations will therefore create the illusion of sound locations in a range of approximately 90 degrees left and right of the central listening axis behind the listener from left and right surround input signals **LS** and **RS**. Referring to FIG. 8, the signal paths for left and right surround signals **LS** and **RS**, only are shown along with the approximate range of perceived rear sound locations **PRSL** from left and right surround signals **LS** and **RS**. Referring to FIG. 2, sounds from left front and right front, input signals **LF** and **RF** will be perceived to remain at approximate sound locations of loudspeakers **LMS** and **RMS** respectively. Therefore in this embodiment of the present invention utilizing loudspeakers located only in front, the listener will perceive apparent sound locations in front and to the rear similar to a conventional surround sound loudspeaker system typically utilizing four actual loudspeakers positioned in front and behind the listener. In addition, this embodiment of the present invention offers advantages over conventional surround sound loudspeaker systems and prior art methods for generating phantom rear channels such as U.S. Patent Nos. 5,799,094; 6,052,470 and 5,579,396 in that the listener will perceive apparent sound locations **PRSL** over a broad range of locations behind them, as shown in FIG. 8, which depend mainly on the composition of the recorded signals rather than apparent rear sound locations which are confined to specific apparent rear speaker locations, such as shown in FIG. 7, which depend mainly on front speaker location. Furthermore, the present invention enjoys advantages in the flexibility of listener location over purely electronic prior art methods for generating a surround sound

illusion. The use of main and sub-speakers according to the present invention eliminates the need for a specific fixed distance relationship between the main speakers and the listener and also between the two main speakers. Additionally, experiments have shown that this arrangement in combination with the signal modifications described herein is capable of generating a broad range of apparent sound locations for listeners located generally in the area in front of the speakers but not located at the principle listening location **LL**. Experiments have also shown that listeners located even further from the principle listening location **LL** may still experience a pleasing surround sound illusion but with much less specific localization of apparent sound locations.

[0048] Referring briefly to FIG. 2b, a variation of this first embodiment is shown which is identical to that shown in FIG. 2 except that a fifth audio input signal, such as a center channel signal in a surround sound system **C** is provided. A center channel loudspeaker enclosure **CSE** which contains at least one center loudspeaker **CS** is also provided. The center signal input **C** for the center channel is transmitted to center loudspeaker **CS**. The sounds produced by center loudspeaker **CS** are perceived by a listener located at the principle listening location **LL** as originating from the approximate sound location of center loudspeaker **CS**. It will be understood by those skilled in the art that in accordance with this and other embodiments of the present invention a surround sound experience from front located loudspeakers may be created using only four audio input signals, as shown in FIG. 2 and FIG. 2b, and that the presence of a fifth audio input signal, such as the center channel signal typically found in a surround sound system, is optional and not required.

[0049] A second embodiment of the present invention is shown in FIG. 10. This second embodiment is the same as the first embodiment described with respect to

FIG. 2 and FIG. 2a, except for the addition of left-right filter 13 and right-left filter 14. Left-right filter 13 is added to the path of left surround signal **LS** after it has passed through front-to-back filter 1, inverter 5, and low pass filter 11, and prior to being combined with right surround signal **RS** in adder 10. Similarly, right-left filter 14 is added to the path of right surround signal **RS** after it has passed through front-to-back filter 2, inverter 6, and low pass filter 12, and prior to being combined with left surround signal **LS** in adder 9. The purpose of left-right filter 13 and right-left filter 14 will be explained with respect to FIG. 9, discussed below.

[0050] FIG. 9 shows a family of curves calculated by subtracting the frequency response shown in FIG. 3 for sounds arriving from a particular direction at the listener's nearest ear from the frequency response for sounds arriving from the same direction at the listener's farthest ear. Therefore, these curves represent the change in frequency response of a sound as it passes across the listener's head from left to right or right to left. By inspection of FIG. 9 it can be seen that these curves are similar in shape and magnitude up to a frequency of approximately 2,000 Hz. Referring again to this second embodiment of the present invention as shown in FIG. 10, left-right filter 13 may have approximately the characteristics of, for example, the curve of FIG. 9 labeled, "45 to -45". Thus, the inverted and low-passed left surround signal produced by right sub-speaker **RSS** for the purpose of canceling IAC will better match the frequency response of the in-phase left surround signal produced by left main speaker **LMS** when it reaches the listener's right ear **Re**, and will, therefore, be more effective in canceling IAC. Right-left filter 14 may have similar characteristics such that the effectiveness of IACC at the listener's left ear **Le**, will be similarly improved. The result will be an improved perception of apparent sound locations over a broad range of locations behind the listener.

[0051] A third embodiment of the present invention is shown in FIG. 11. The third embodiment is identical to the second embodiment described with respect to FIG. 10, except that high-pass filters **15** and **16** are added. High-pass filter **15** is added to the path of left surround signal **LS** after it has passed through front-to-back filter **1**, inverter **5**, low-pass filter **11**, and left-right filter **13**, and prior to being combined with right surround signal **RS** in adder **10**. Similarly, high-pass filter **16** is added to the path of right surround signal **RS** after it has passed through front-to-back filter **2**, inverter **6**, low pass filter **12**, and right-left filter **14**, prior to being combined with left surround signal **LS** in adder **9**. In general, there is very little difference between left and right surround signals **LS** and **RS** at low frequencies. Referring to Fig. 10, the signal manipulations described in the second embodiment have little effect on the signals below a frequency of approximately 150 Hz except that one component of these signals is inverted before being added to the opposite side surround signal by adders **9** and **10** and transmitted to their respective sub speakers **LSS** and **RSS**. Therefore the low frequency response of these components will substantially cancel each other when they are added together leaving a signal composed mainly of mid and higher frequency information to be reproduced by sub speakers **LSS** and **RSS**. As discussed previously, directional hearing on the basis of ITD's is effective only down to a frequency of approximately 150 Hz. Referring again to FIG. 11, frequencies below approximately 150 Hz may be eliminated from the inverted left and right surround signal paths through the use of high-pass filters **15** and **16**, without compromising the effectiveness of IACC. Therefore the low frequency response of the in-phase portion of the left and right surround signals will not be canceled and the low frequency performance of the system, overall, will be improved.

[0052] A fourth embodiment of the present invention is shown in FIG. 12. In this embodiment of the present invention the center loudspeaker is eliminated from the first embodiment shown in FIG. 2b and described above. Referring to FIG. 12, center signal input **C** is split and added to left and right front signals **LF** and **RF** and to modified left and right surround signals **LS** and **RS**, by adders **3** and **4**. The resulting signal is transmitted to left and right main speakers **LMS** and **RMS**, respectively. The listener will, therefore, perceive a phantom center sound location **PCS** directly in front and on the central listening axis **CLA** for sounds from the center signal input **C**, without the use of a center loudspeaker. It will be understood that within the scope of the present invention the technique described above for generating a phantom center sound location and eliminating the physical center speaker may be employed as part of any of the other embodiments described herein.

[0053] A fifth embodiment of the present invention is shown in FIG. 13 and FIG. 13a. This embodiment of the present invention is similar to the first embodiment described with respect to FIG. 2, except that left and right front signals **LF** and **RF** are applied to the left and right sub speakers **LSS** and **RSS** through certain filters and signal manipulations so as to cancel IAC and create an expanded range of perceived front sound locations in addition to the perceived range of rear sound locations previously discussed in the first embodiment. Referring to FIG. 13, left front signal **LF** is combined with left surround signal **LS** by adder **3** after left surround signal **LS** has been modified by front-to-back filter **1**. Similarly, right front signal **RF** is combined with right surround signal **RS** by adder **4** after right surround signal **RS** has been modified by front-to-back filter **2**. The combination of left front signal **LF** and modified left surround signal **LS** is transmitted to left main speaker **LMS** and is also subtracted from the combination of right front signal **RF** and modified right surround

signal **RS** by first inverting the combined left front plus modified left surround signals with inverter **5** and, after passing through optional low pass filter **11**, is added by adder **10** to the combined right front plus modified right surround signals which have further passed through optional low-pass filter **8**. The resulting difference signal is transmitted to the right sub-speaker **RSS**. Similarly, the combination of right front signal **RF** and modified right surround signal **RS** is transmitted to right main speaker **RMS** and is also subtracted from the combination of left front signal **LF** and modified left surround signal **LS** by first inverting the combined right front plus modified right surround signals with inverter **6** and, after passing through optional low pass filter **12**, is added by adder **11** to the combined left front plus modified left surround signals which have further passed through optional low-pass filter **7**. The resulting difference signal is transmitted to the left sub-speaker **LSS**. As discussed above, the effect of front-to-back filters **1** and **2** in the signal path of left and right surround signals **LS** and **RS** causes them to be perceived as located behind the listener. The absence of these filters in the path of left and right front signals **LF** and **RF** causes them to be perceived as located in front of the listener. The arrangement of main and sub-speakers, **LMS**, **RMS**, **LSS** and **RSS**, combined with the signal manipulations shown in FIG. 13 causes the listener to perceive an expanded range of sound locations for all of the signals applied to main and sub-speakers with sound locations from left and right front signals **LF** and **RF** perceived as in front of the listener and sound locations from left and right surround signals **LS** and **RS** perceived as being behind the listener as shown in FIG. 14.

[0054] In accordance with this fifth embodiment FIG. 13a shows the general composition of the modified and combined signals transmitted to each speaker where the prime designation, ' , denotes that the original audio input signal has been suitably

modified by signal modification and combination means **20**. It will be understood that within the scope of the present invention and as shown in FIG. 13a that any suitable means may be employed to achieve the appropriate signal modifications and combinations.

[0055] A sixth embodiment of the present invention is shown in FIG. 15. In this embodiment of the present invention, a signal format detection device **22** is added to the method shown in FIG. 13 and described above as the fifth embodiment and adders **17** and **18** are replaced by switches **19** and **19a**. When signal format detection device **22** determines that at least four audio input signals are present, switches **19** and **19a** are activated to select the signal paths originating with left and right surround signals **LS** and **RS**. In this case the result is as described above in the first embodiment. When signal format detection determines that left and right surround signals **LS** and **RS** are not present, switches **19** and **19a** are activated to select the signal path originating with left and right front signals **LF** and **RF**. In this case the result is an expanded range of perceived sound locations in front of the listener for reproduced sounds associated with left and right front signals **LF** and **RF** as shown in FIG. 16. It will be understood that signal format detection and suitable switching may be used to reroute any pair of input signals for the purpose of creating a broader perceived range of sound locations either in front or behind the listener.

[0056] A seventh embodiment of the present invention is shown in FIG. 17. In this embodiment of the present invention a rear center channel signal input **RC** is added to the embodiment described with respect to FIG. 11. Rear center channels have become increasingly common in so called "6.1" surround sound systems. Rear center signal **RC** is modified by passing through center front-to-back filter **21** and is then combined on one side with left front signal **LF** and left surround signal **LS** by adder **3**

before being passed to left main speaker **LMS** and on the other side with right front signal **RF** and right surround signal **RS** by adder 4 before being passed to right main speaker **RMS**. If the center front-to-back filter 21 has characteristics, for example, approximately similar to front-to-back filters 1 and 2, the rear center channel signal emanating from left main speaker **LMS** and right main speaker **RMS** will be perceived by a listener located at principle listening location **LL** as having frequency response approximately the same as if these sounds were originating behind the listener at locations mirror image to the locations of left and right main speakers **LMS** and **RMS** shown as locations **PLMS** and **PRMS** in a simplified diagram FIG. 18. Since the phantom rear sounds from locations **PLMS** and **PRMS** are the same, a listener located at listening location **LL** will perceive the rear center signal as emanating from a phantom rear center location **PRCL** directly behind the listening location as also shown in FIG. 18.

[0057] An eighth embodiment of the present invention is similar to the first embodiment as shown in FIG. 2 except that no front-to-back filters are used. Referring to FIG. 19, the signal paths for left and right surround signals **LS** and **RS** are shown without front-to-back filters. All other signal paths are the same as shown in FIG. 2. In the absence of front-to-back filters, left and right surround signals **LS** and **RS** will be perceived by a listener located at principle listening location **LL** as emanating from a range of locations in front of the listener indicated in FIG. 19 as **PSSL**. As in the first embodiment left and right front signals **LF** and **RF** are fed to left and right main speakers **LMS** and **RMS**. As a result a listener located at listening location **LL** will perceive left and right front signals **LF** and **RF** as originating from a range of sound locations **PFSL** between said left and right main speakers **LMS** and **RMS** while left and right surround signals **LS** and **RS** will be perceived emanating

from a range of locations in front of the listener **PSSL** extending beyond the locations of the loudspeakers. Experiments have shown that this arrangement produces an acceptable pseudo surround sound experience due to the broad range of perceived sound locations for surround signals **LS** and **RS** even though they are perceived as emanating from in front and to the sides of the listener rather than to the rear.

[0058] A ninth embodiment of the present invention is shown in FIG. 20. This ninth embodiment is similar to the first embodiment except that separate left and right front speakers **LFS** and **RFS** are provided for reproducing left and right front signals **LF** and **RF**. Left and right front speakers **LFS** and **RFS** may be placed anywhere in front of the listener and receive only the left and right front signals **LF** and **RF** respectively. As a result, a listener located at the principle listening location **LL** will perceive that left and right front signals **LF** and **RF** are emanating from a range of sound locations **PSSL** between the left and right front speakers **LFS** and **RFS** in front of the listener. In this ninth embodiment signal modifications and combinations are applied to left and right surround signals **LS** and **RS** by signal modification and combination means **20** to produce the signal combinations for each speaker as shown in FIG. 20. Signal modifications may include any of the modifications discussed previously in other embodiments; for example only and not by way of limitation, front-to-back filters, left-to-right filters, low-pass filters or high-pass filters, such that the listener perceives a broad range of apparent sound locations for left and right surround signals **LS** and **RS** either in front or to the rear of the listener according to the signal modifications employed.

[0059] A tenth embodiment of the present invention is shown in FIG. 21. This tenth embodiment is similar to the first embodiment described in FIG. 2 and FIG. 2a except that the at least four input signals **LS**, **LF**, **RF** and **RS** are derived from two original

input signals **L** and **R** such as are typically found in a stereo audio system. In this tenth embodiment two channel to multi-channel conversion means **22** are provided which process the two original input signals **L** and **R** in such as way as to provide at least four signal outputs **LS**, **LF**, **RF** and **RS**. Many methods for accomplishing the two channel to multi-channel conversion, such as Dolby™ Pro-Logic™, are known to those skilled in the art. These at least four signal outputs **LS**, **LF**, **RF** and **RS** are then used as inputs to the signal modification and combination means **20** described previously in the other embodiments. As a result, a listener located at the principle listening location **LL** will perceive a surround sound experience from only front located loudspeakers and from only two original input channels **L** and **R** similar what is described in the other embodiments. It will be understood that within the scope of the present invention the two channel to multi-channel conversion means **22** may also produce a fifth channel, such as a center channel **C** or a sixth channel, such as a rear center channel **RC**, which would also be used as inputs to the signal modification and combination means **20** described previously in the other embodiments.

[0044] In addition to these embodiments it will be understood that many other variations are possible within the scope of the present invention. For example the enhancements described above as the second and third embodiments may be combined with the fourth, fifth and sixth embodiments. Or, the phantom center channel method described in the fourth embodiment may be combined with any of the other embodiments. It should also be understood that within the scope of the present invention, the input signals are not limited to left surround, right surround, left front, right front and center, such as are available in a typical audio surround sound system, but may be any combination of at least two signals where it is desirable to create a broad range of perceived sound locations either in front of or behind a listener.